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On Electrical Design and Technical Performance Requirements for Large Scale Wind Farms

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***Abstract*— This paper presents and discusses technical performance requirements for connection of large scale wind turbine generating systems into HV transmission networks. Requirements have been presented for the purpose of achieving performance enhanced operation, reliability and assessment of the power plant operating limits for ensuring power system security at the high voltage point of connection. Experiences presented here refer mainly to few of the selected technical requirements and issues encountered during the process of wind farms connections into Eastern Australian power system. In particular the paper presents and discusses issues with respect to requirements for provision of reactive power, voltage and frequency control as well ride through capabilities subject to disturbances following contingency events.**

I. INTRODUCTION

The interaction between wind generation and the power system must be coordinated for achieving performance enhanced quality of supply and reliability to end user consumers. The technical envelope under which wind farm proponents seek connection (or access) into Eastern Australian interconnected system is done according to Performance Standards specified as part of the NER (National Electricity Rules) and guidelines set out by AEMC (Australian Energy Market Commission), NEMMCO (known as AEMO from July 2009-Australian Energy Market Operator) and where necessary relevant guidelines or codes of practice issued by Transmission System Operators. Performance standards specify a range of technical requirements classified under either Automatic Access, Minimum Access or Negotiated Access Standard, which form the basis of the technical terms, conditions and assessment of the Connection Agreement between the Wind Farm owner and the TSO operator providing the HV connection point. The automatic access standard in general specifies the maximum requirement that the wind farm owner must satisfy with respect to design and compliance of its generating facility and associated protection and control equipment. Assignment to a particular access standard requires extensive system design and modelling studies with respect to assessment of wind farm control capabilities, protection, ride through and network (stability) interconnection limitations. This paper addresses only few of those technical performance standards, mainly those related to voltage, reactive power and frequency ride through requirements. A full scope of requirements and guidelines on model performances are set out by AEMC and NEMMCO (AEMO) [1,2]. Apart from those Rules set explicitly in [1,2] all wind farm design and installation work should be done and tested in accordance with the requirements of the appropriate Australian Standard (AS), current on the date of the Contract. Where an Australian Standard does not exist, the relevant IEC Standard would normally apply. Where no relevant AS, IEC Standard exists the plant should comply with recognised standards of good practice.

II. REACTIVE POWER CAPABILITY

The automatic access standard requires a provision of reactive power supply and absorption capabilities at POC which are at least 39.5% of total registered active power production level of the wind farm. The wind farm operator must meet this capability at any active power output and voltage range limits specified under the Rules for connection and compliance purposes. In particular (typically) the standard must be met for voltage levels within 10% of 'normal' without any contingency events. During credible contingency events, the voltage levels should not rise more than 30% and those levels shown in Figure 1. It has to be pointed out that the design engineer must seek confirmation from Network Operator on voltage levels classified as 'normal' or 'nominal'. Misuse or misinterpretation of these levels (if not defined to be referring to the same) can cause severe protection system setting and plant performance inadequacies. Likewise the difference in normal-nominal levels must be accounted in the design and operation of equipment, e.g. the transformer at the connection point would have to rated at adequate tapping range to account for higher/lower normal operating voltage levels. It is TSOs responsibility to provide voltage supply limitations and target values for control of voltage at POC. In the case that a number of users share the HV TSO switching/sub station, then the TSO must establish and provide target voltage and limit values which could vary depending on the total aggregate loading level seen at HV switching/sub station. It is quite common to connect a wind farm collector substation via transmission circuit into HV TSO network via the provision of switching station at the cost of the wind farm developer. In the case of connection to existing HV TSO owned substation, it could be just enough to provide terminating gantry structures at HV substation and establish it as POC for the wind farm assuming that the MV/HV Transformer is located inside the collector substation, in the wind farm area itself. For this purpose the entire voltage drop across all conductors in the reticulation system of the wind farm must be considered by the design engineer.

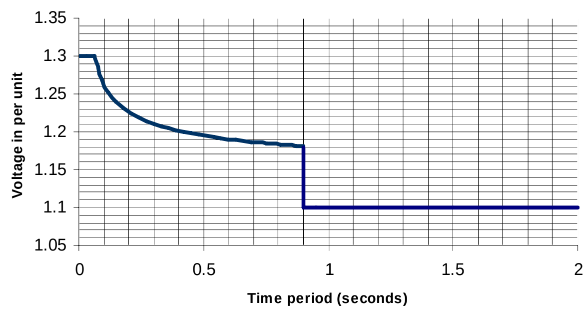

Fig 1. Allowable voltage deviation at POC from 'normal' as a consequence of a credible contingency event

As an example, under this reactive capability standard, a wind farm registered at a value of 250MW supply capacity, must have continuous capability to supply and absorb at least 98.75MVar at its high voltage POC. The value of at least $\pm$98.75MVAr would apply if the same wind farm (250MW) was to operate at 100MW or any other point under its PQ capability chart. The design engineer must ensure that all aspects of the wind farm and its associated equipment be modelled and analysed to conform to this standard. The extent of PQ WTG capability, together with step up transformer losses, reticulation network, collector substation and primary equipment including reactive compensation devices need to be assessed. Typically a number of steady state-loadflow studies needs to be performed assessing low, nominal and high voltage profiles across the interconnecting wind farm/TSO's network. The study needs to consider different levels of active and reactive power outputs of turbines and capacitive/inductive nature of wind farm reticulation network, losses, transformer, tap range, compensating equipment, load levels, network line outage scenarios etc. If the automatic access standard cannot be met at POC, then a proposal for unity pf operation can be considered and approval needs to be sought from TSO and NEMMCO. A wind farm design engineer should also be aware that design of equipment under diversified range of studies may not ensure dynamic compliance with respect to low voltage ride through requirements. Where applicable the design engineer should seek information from WTG supplier on reactive power capability variation of WTGs as a function of active power output due to design characteristics of the plant. Equally, the capabilities of the WTG, fixed shunt, switched shunt caps/reactors or any combination of these should be considered during the design process. The type of reactive compensation could form any combination of mechanically switched devices, STATCOMS, SVC's, transformer tap changer capabilities etc. During some dynamic studies, and depending on network topological changes considered by the design engineer, dynamic compensating equipment can cause intolerable overvoltage scenarios as a result of excessive reactive current injection during dynamic (network) events. As an example, a response of the wind farm during sudden phase changes in the HV TSO' network (sudden power flow change due to a line outage) can be considered. Under these conditions, occurrence in over voltage could be observed and hence proper design of reactive compensating equipment and their controllers needs to be analysed and understood in detail. In particular, a brief list of items needed for consideration in determining reactive power capability of the wind farm, consists of: characteristics of POC, X/R ratios, reticulation network design (distances to WTGs), flicker and voltage step limitations, pf capability, step up Transformer details, range of TSO' HV Thevenin equivalent network impedance, any currently present reactive compensation within the network, planned network developments, planned generation, load profiles etc. As a secondary requirement to these, the wind farm design engineer needs to consider other associated requirements, such as: voltage control requirements, pf control, rise and response times, damping, response requirements to voltage disturbances etc.

Reactive power requirements in the power system are dependant on location and voltage control requirements. Under certain network conditions, it may be needed to curtail total wind farm production so that voltage constraints can be satisfactorily applied. It is important that the design engineer assess the connection agreement between the wind developer and TSO and make clarifications on generation dispatch curtailment.

Our experience has indicated different capabilities in technologies provided by DFIG and full load converter wind turbine manufacturers. While most of our considerations have been on AC type connections, any proposals for HVDC links would also have to be analysed and capacity for reactive power control of HVDC pole converter-inverter stations should also be modelled/assessed together with associated limiting capabilities. At present HVDC technology seems to be financially unjustified option for (onshore) wind farm proponents seeking connections in the Australian National Electricity Market.

While the choice of WTGs is mainly based on wind farm proponents' financial-investment decisions considered throughout the tender process of WTG submissions review, the 'Owners' engineer acting on behalf of farm developers should also consider network imposed limitations and/or capabilities which could be critical in making decisions about the most adequate WTG technology for the point of connection.

Obtaining the network information can be a difficult task and certain Transmission system operators may have preferred choice in carrying out Connection Application process and the amount of information that gets provided to Wind Farm proponents and associated contracted Owners engineers.

Typically and at the very least, Thevenin equivalent network should be provided by the TSO or DSOs. Equally a full range of possible impedances seen from the generator side should be provided for determination of appropriate fault levels and reactive power and dynamic studies. Certain TSO's prefer to undertake (modelling/analysis) assessment of performance standards themselves. While this is welcoming, it is equally important that studies be undertaken by the proponents of the wind farm so that any inconsistencies can be resolved and agreed on by both parties.

In determining the design of reactive power compensating equipment or wind farm equipment characteristics needed to meet reactive power capability standard, design engineer must also take care of the total cost for installation and practicality of reactive equipment. For example, consider the total reactive minimum reactive requirement for 250MW wind farm at $\pm$98.75MVAr. This is the total value requirement according to the standard, and may not be the actual (maximum) value that a wind farm operator may operate at. It would greatly assist in the design of such equipment if the design engineer has relevant network information. Such information could consist of present (extended) network (and not just single machine infinite bus system) information, and any short term, mid term and/or long term network developments or planned (or assessed) generation interconnections, regional load and supply profiles, interconnector flows etc. Typically in Australia, some planned, short term network extensions and generation connections can be obtained from NEMMCO and for example relevant TSO's annual planning reports. In some cases due to voltage stability constraints in interconnecting networks, it may not be practical to make a big investment in reactive compensating equipment if the wind farm could satisfy other grid code requirement and still maintain adequate voltage profiles at its POC. It may be just enough to provide 50MVAr of reactive equipment instead of minimum 98MVAr, as an example. From experience, downsizing on reactive equipment can be most beneficial financial option in reducing some of the overall project investment costs. As an example typical collector substation transformer can cost in the order of few million dollars while the full scope of reactive compensating equipment at collector MV side can be in excess of 200% or even 300% of the transformer supply price. Likewise, any associated reactive equipment such as SVC transformer, harmonic filters, TSC and TCR, protection, control buildings etc need to be absorbed in the overall cost. Despite the network constraints, any reactive plant equipment installed is absorbed into the overall capital cost investment that would normally be part of equipment assets for wind farm operator.

III. Generating Unit Response to Voltage Disturbances

The standard specifies a range of voltage ride through level requirements at the POC such that the wind farm and each associated WTG unit remains online for the following:

- Voltages over 110% and those levels and times specified in Fig 1.
- +/-10% of normal voltage continuously
- 80% to 90% of normal voltage for at least 10s
- 70% to 80% of normal voltage for at least 2s.

As it has been discussed under the Reactive Capability Standard, the design engineer should clarify the difference (if any) between the levels labeled as nominal and those referred to as normal by transimssion system operators. For example, TSO could advise that 500kV POC level would be regarded as normal at value of 525kV as expected range of operation, equally it is quite common to operate the 132kV network at 140kV etc. In that respect the wind farm engineer should ensure all equipment ratings conform to this requirement. For example MV/HV transformer (and tapping range) would have to allow for the higher operating voltage range. Typically WTG manufacturers supply over-voltage and under-voltage protection settings for each generating unit. These levels together with their trip time (trip time = trip delay + activation time) need to be considered. In many cases protection settings may not be specified at particular voltage level sought under this standard, i.e. relay could be set at 0.85 pu or even 0.5 per unit for a certain trip time. Also the trip times may not be conforming to those required under the standard. It has to be pointed out that this standard requires voltage ride through capability at POC and the levels are not specified at each WTG unit. In the case that WTG units have protection settings different from standard levels specified (and also not according to time delays required) it is still possible to register and design the wind farm to comply with the automatic standard requirements. This can be achieved by using adequate (fast acting) reactive compensating equipment at the MV or HV wind farm/TSO level to prevent the wind generator terminals from being exposed to high or low transmission system voltages. Alternativelly, a change in WTG protection settings range can be discussed with the WTG manufacturer. The design engineer should cary out dynamic set of studies with properly modelled WTG and interfacing network to demonstrate the wind farms level of compliance with this requirement. In the case that automatic access standard cannot be met, the minimum access standard could be negotiated with TSO and NEMMCO which requires voltage to frequency ratio at POC to be less than equal to 1.15 and less of 2 min duration; and 1.10 and less of 10mins duration for voltage profiles within +/-10% of normal voltage levels.

In some cases, conformance to this (automatic or minimum) standard could equally require TSO to modify protection clearance times of existing network subject to a number of network operating dynamic scenarios.

Generally it is just enough to confirm relay protection settings of WTG units and any other protection system in the wind farm itself. Reactive compensation equipment should also be considered if needed to meet this standard and avoid causing undesirable voltage stresses on WTG units. A set of studies may also be needed to demonstrate conformance to this requirement and equally the wind farm and each of its associated WTG units would be subject to ongoing compliance requirements under this standard for the operational lifetime of the plant.

IV. GENERATING SYSTEM RESPONSE TO DISTURBANCES FOLLOWING CONTINGENCY EVENTS

This standard requires the wind farm and each of its WTG units to remain online for a variety of system disturbances/faults. In assessing this standard, the wind farm design engineer should implement PSSE or PowerFactory models of the wind farm system, including details of WTG units and all associated controls, limiters, reactive power devices, assessment of protection settings etc. The standard provides general guidelines and requirements with respect to fault clearance times of primary and back up protection equipment that should be met by the wind farm proponent and depending on the transmission voltage levels at POC, they are given in Table 1.

TABLE I
FAULT CLEARANCE REQUIREMENTS FOR PRIMARY AND BACKUP PROTECTION

Nominal Voltage @ Fault Location	Fault clearance time (ms)	
	Primary Protection	Backup Protection
400kV and above	80	175
At least 250kV and less than 400kV	100	250
Greater than 100kV and less than 250kV	120	430
100kV and less	As necessary to meet stability and prevent plant damage	

For example, the primary system protection should clear the fault within a substation, within connected plant or at least the half of the line near the protection system by 80ms on transmission network considering 400kV and greater transmission voltage levels. In the case of a fault covered by the primary protection which is anywhere on the remote portion of the line covered by such protection, fault clearance times are expected to be met within 100, 120 and 220ms for nominal (descending order) voltage levels given in Table 1. The standard also specifies during-the-fault and post-fault requirements that the wind farm should meet at its POC:

- During the fault, the wind farm at its POC must inject increased reactive current and for each 1% during the disturbance voltage reduction level, the wind farm must deliver 4% of the maximum continuous current of each operating WTG unit.
- Upon fault clearance, the wind farm should provide enough reactive capability to stabilize the voltage to within its allowable range at POC. In the post-fault period (100ms) the wind farm must restore its active power levels to at least 95% of the pre-fault production level.

The assessment of this standard does not only involve application of short circuit fault at POC, it is also critical to analyse and conform to TSO operational arrangements and assess performances under abnormal network conditions, For example, the scope of work could consider the following:

- Solid 3 phase short circuit fault in the network cleared by breaker-fail protection time settings (e.g. 250ms for 330kV network) followed by the subsequent loss of another HV transmission circuit (subject to data availability to wind farm design engineer).
- Solid 3 phase bus fault cleared by breaker-fail protection at POC of the wind farm
- Loss of generation and load rejection studies

The study must consider the full rated output of the wind farm. Submission of the study assuming reduced operating wind farm scenario can be included as complimentary to the full production level study. The study should normally form the part of the so called Design Report for the wind farm and inclusion of all relevant plots and assumptions must be stated. This should also be provided to TSO and NEMMCO as part of documentation in support of the performance demonstrations according to the Rules. It is suggested that the design engineer should provide time domain responses of wind farm and turbine parameters, including active and reactive powers, voltage profiles, relevant control signals, control system limitations, protection settings etc.

From experience the fault ride through function of the WTG units is placed in the frequency converter. The pilot control scheme for the wind farm is realized globally via wind farm's SCADA system. A number of feedback control loops is typically included to account for reactive power control, voltage control and active power/frequency control. Reference tracking signals are individually communicated to each WTG unit controller system.

For DFIG type units, converters form only a portion of the total WTG rating (for example 30%). It is necessary to document crowbar protection functions and any such converter limitations during system dynamic studies and analysis of WTG units with respect to system faults. Documentation should be provided by the design engineer to include description and behaviour of converter system limitations.

The response of the WTG units depends on pre-fault levels, the nature of the fault and any DC link converter voltage limitations. The controller should be able to detect transition from steady state and fault situations. The voltage of WTG terminals need to recover sufficiently for the controller to switch back into normal operation.

The standard does not only require analysis of system responses with respect to 3 phase short circuit faults. Equally the standard requires assessment of wind farm performances in the case of single phase and faults involving combination of phases. The design engineer should document all 3 phase voltage variations at LV, MV and HV connection points due to system unbalanced faults. From experience this can be particularly useful in assessing if unbalanced fault could exceed under-voltage protection set point at WTG terminals in Va, Vb and Vc phases. However for the purpose of wind farm connection, 3 phase short circuit fault must also be considered. In general TSO planning guidelines only consider 2 phase to earth faults as the most likely event in HV transmission systems. This criterion is normally used based on operational experiences but could vary from one operator to another. The wind farm engineer must coordinate with the TSO the design of its protection settings to allow for minimized risk of slow fault clearances. Likewise the wind farm engineer should also be aware if the fault protections will be cleared by the faster of the duplicate protections (with installed intertrips available).

Depending on network characteristics, wind turbine topology, reactive compensation equipment, protection and control capabilities, the wind farm proponent can also seek approvals for meeting the minimum or negotiate access standards. This part of negotiation would involve TSO and assessments undertaken by NEMMCO which could demonstrate the feasibility of requirements imposed by the automatic access standard or otherwise agreed acceptable by the TSO.

In obtaining compliance or at least an indication to the requirements of this standard, the design engineer must be familiar with the full scope of available control functionalities in the pilot Park control scheme of the wind farm. Control settings for active and reactive power production capabilities could be readjusted so that wind farm does not negatively contribute to potential voltage instability scenarios as a result of a system related fault. For example active power production levels could be slowly ramped up following up severe system fault. Ramping up of active power production could be done through pilot control scheme and each individual WTG unit controller. This type of scheme as an example could allow automatic return of reactive power levels in the post fault period necessary enough to stabilize system voltage, followed up by ramping active power characteristics. There could be other means of maximally optimizing ride through capabilities of the wind farm subject to network contingency events and therefore the wind farm engineer should be familiar with the full scope of controls and capabilities of WTG equipment and main pilot park control schemes.

Part of the requirement under the Rules requires provision of post-connection system data. This data, normally known as R2 data is collected during wind farm commissioning. Those aspects that seem impractical to tests due to network and protection system constraints are normally demonstrated by way of mathematically modelled responses in PSSE and PowerFactory software, and the performance of the wind farm and each of its WTG units would be subject to ongoing compliance requirements specified under the Rules and Connection Agreement between the wind farm owner and TSO. The ongoing compliance matters can be captured by the installation of disturbance recording equipment and observation of trigger flags in wind farm protection systems. It is the requirement for the wind farm proponent to undertake site tests sufficient to verify parameters of WTG and associated control systems. Normally signal reference step injection tests are taken as part of R2 data collection and model parameter derivation from R2 staged tests. In respect to this standard, short circuit faults are not performed due to stability and network imposed constraints which could be quite different from practices in Europe. If however the wind manufacturer prefers to demonstrate model validation and parameter estimation test under the ‘Fault Ride Through Control Systems’ requirement, then such tests could be adjusted to allow for off-site type-test for which the following should normally be considered, or as otherwise required by the wind farm manufacturer:

- Application of 3 phase fault or 2 phase to earth fault
- The WTG unit tested should be identical to the one installed on site, including the applied setting in the control system. In the case of difference in settings applied during the test, then the wind farm design engineer or manufacturer should translate such test responses into appropriate model parameters for WTG units installed onsite.

It has to be pointed out that model validation in Europe (For example see Energinet.dk / Eltra standard on wind farm connections, Denmark) with respect to fault ride through capability is carried out by injection of voltage time series, i.e. the wind farm is assumed to be connected to a voltage controlled bus. This approach could have advantage in model validation of WTG units since it does not require the wind farm design engineer to have detailed knowledge of power system operating conditions and dynamics external to the wind farm’s POC. This type of methodology is not currently considered under the Rules requirement in Australia. Thus in the case of analysis of wind farm with respect to measurement taken from disturbance recorders, the design engineer must be careful in distinguishing those dynamics associated with the wind farm and those coming from the network side. This can be a very difficult task and at present there are no detailed guidelines for assessment of WTG units under those circumstances apart from performance requirements defined under the technical envelope of each standard outlined in the Rules.

V. Wind farm response to Frequency Disturbances

The frequency operating standards have been established by the Reliability panel [1]. Standards are defined for mainland Australia and Tasmania. For mainland eastern Australian interconnected system, frequency operating bands for both normal and islanded system situation are listed in [1]. Limits are established according to operational system levels which consider a number of network conditions for which stabilization and recovery times apply to the region in which wind farm unit is located. The applicable (mainland) frequency operating bands are listed in Table 2 and Table 3. According to the standard, the wind farm and each WTG unit must be capable of continuous uninterrupted operation during frequency excursions within the following range:

- 47-49 Hz, 51-52 Hz for at least 2 minutes
- 49-49.5 Hz, 50.5-51 Hz for at least 10 minutes
- 49.5-50.5 Hz for indefinite time

The Wind farm and all of its associated WTG units must be capable of continuous operation under this standard unless the rate of change of frequency is greater than the range of +/- 4Hz/s for more than 0.25 s. The wind farm design engineer must confirm that the design protection settings for o/f and u/f protection trigger levels are set accordingly to comply with the frequency limitations outlined in the standard.

TABLE II

FREQUENCY OPERATING LIMITS FOR MAINLAND AUSTRALIA

Condition	Containment	Stabilisation	Recovery Time
no contingency event or load event	49.75 to 50.25 Hz, 49.85 to 50.15 Hz 99% of the time	49.85 to 50.15 Hz within 5 min	
generation event or load event	49.5 to 50.5 Hz	49.85 to 50.15 Hz within 5 min	
network event	49 to 51 Hz	49.5 to 50.5 Hz within 1 min	49.85 to 50.15 Hz within 5 min
separation event	49 to 51 Hz	49.5 to 50.5 Hz within 2 minutes	49.85 to 50.15 Hz within 10 min
multiple contingency event	47 to 52 Hz	49.5 to 50.5 Hz within 2 min	49.85 to 50.15 Hz within 10 min

TABLE III

FREQUENCY OPERATING LIMITS FOR POWER SYSTEM ISLAND IN MAINLAND AUSTRALIA

Condition	Containment	Stabilisation	Recovery Time
no contingency event or load event		49.5 to 50.5 Hz	
generation event or load event	49 to 51 Hz	49.5 to 50.5 Hz within 5 minutes	
The separation event that formed the island	49 to 51 Hz or a wider band notified to NEMMCO by a relevant Jurisdictional Coordinator	49.0 to 51.0 Hz within 2 minutes	49.5 to 50.5 Hz within 10 minutes
Multiple contingency event including a further separation event	47 to 52 Hz	49.0 to 51.0 Hz within 2 minutes	49.5 to 50.5 Hz within 10 minutes

Figure 2 illustrates the frequency ride through requirements under the automatic access standard as required by the Rules.

Typically from experience, WTG units come with o/f and u/f protection settings which allow the turbine to ride through frequency bands between 47.0 and 52.0 Hz. The design engineer must ensure that frequency standard must be met by trigger levels set out for each WTG unit. Trigger levels for frequency relays, trigger delay times (typically 10 cycles above/below 47 and 52 Hz) as well as Hz/s rate of change trigger must be considered by the design engineer and submitted as part of the unit protection scheme documentation

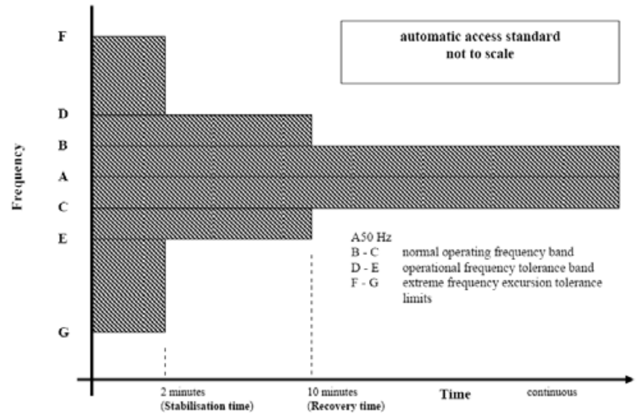

Fig 2. Frequency Ride Through Requirement under the Automatic Access Standard of NER

The frequency operating bands for mainland Australia are defined as follows, Table 4:

TABLE IV

FREQUENCY OPERATING BANDS FOR MAINLAND AUSTRALIA

Frequency Band	Normal Hz Range	Island Hz Range
Normal operating Band	49.85 to 50.15	49.5 to 50.5
Normal Operating Excursion Band	49.75 to 50.25	49.5 to 50.5
Operational Tolerance Band	49.0 to 51.0	49.0 to 51.0
Extreme Excursion Tolerance Band	47.0 to 52.0	47.0 to 52.0

Typically the completion of the wind farm from its initial feasibility and siting study to the full operational completeness level can take up to few years. The performance standards relate to an agreement between TSO and the wind farm proponent at time of execution of the Connection Agreement. While the design and assessment of the wind farm is normally done according to at time valid NER version, the frequency operating standard can be enforced by NEMMCO (and supported by TSO) to include the latest operating frequency standards as continually monitored and updated by the AEMC Reliability panel.

Together with the protection trigger levels for each WTG, the design engineer must also be aware of the total generating capacity that can be installed as a result of frequency limitations imposed by the Reliability Panel. For example restrictions due to maximum allowable generator (plant) contingency event must be considered as well. In Tasmania 144MW level has been in the past discussed as the maximum generator contingency level, see [1] for further details. This can place severe limitations on the total size of the project intended for connection as a result of frequency operating standards. TSOs have well established emergency procedures for load shedding schemes, however under the market rules for compensation, it may not be justified by the TSO to accept responsibility of finding acceptable load for shedding purposes. In this case, for example, the wind farm owner would have to contract the load customer willing to shed its load as a result of generating plant contingency event. Therefore it is suggested that the design engineer carefully confirms with TSO and NEMMCO any frequency standard related restrictions with respect to generator contingency events or any other events that could be put at the cost of wind farm developer. The burden of such development could be related not only to finding and paying the customer in the case of load shedding-generator contingency event, but such protection scheme would also require set up of adequate communication links, protection equipment coordination, as well as extensive dynamic system studies considering a number of operating (network and generating plant) scenarios. Under these circumstances it is only expected that TSO/NEMMCO would perform such studies at proponent's expense. The frequency operating standard also allows for consideration of minimum access standard and negotiations with TSO and NEMMCO for cases where wind farm proponent cannot meet automatic access requirements. Frequency ride through requirements are illustrated in Fig 3.

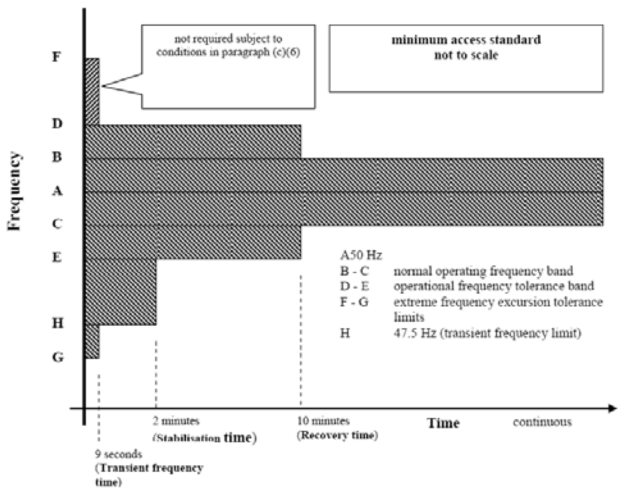

Fig 3.Frequency Ride Through Requirement under the Minimum Access Standard of NER

The so called transient frequency limit and transient frequency times are used which map the limits specified by 47.5Hz and 9 seconds respectively. The standard applies unless the rate of change in frequency is outside the range of +/-1Hz/s for more than 1 s. The standard value of 9 seconds has been recently updated from an older value of 20s. Under the new standard, this implies that the generator plant could trip after 9 seconds of low frequency ride through level instead of 20s as required by some older NER versions. Tighter limits on time could cause some problems with respect to coordination of load shedding schemes in some TSO or DSO parts of the network. In general, and as per the Rules, it is network operator's responsibility to coordinate load shedding schemes as a result of time limits suggested by the Reliability Panel, unless there are other constraints, such as generator contingency situations discussed previously, which could impact on the wind farm developer/owner.

VI. FREQUENCY CONTROL

The standard specifies requirements for provision of exchange levels in active power outputs at POC of the wind farm with respect to system frequency variations. In particular the standard requires active power control capabilities of the wind farm to comply with the following:

- The active power output of the wind farm at POC must not change during the changes in system frequency which are within the nominal frequency band, as determined by the Reliability panel.

During system frequency excursions above the upper limit of the normal operating frequency band, the wind farm must reduce its total active power at POC, which is at least:

- 0.2xPMAXxΔf where Δf is the percentage difference between the system frequency and the upper limit of the normal operating frequency band.
- 0.1xPMAX.
- Po-PMIN, or zero if Po-PMIN < 0.

During system frequency excursions below the lower limit of the normal operating frequency band, the wind farm must increase its total active power at POC, which is at least:

- 0.2xPMAXxΔf where Δf is the percentage difference between the lower limit of the normal operating frequency band and system frequency.
- 0.05xPMAX.
- 0.333x(PMAX-Po), or zero if PMAX-Po < 0.

Where PMAX is the maximum possible operating (nameplate) level of the wind farm; PMIN is the minimum possible sent out active power level of the wind farm, assuming all WTG units in service, and, Po is the pre-disturbance active power level at POC of the wind farm. Typically for large scale wind farm installations, frequency control functionality at the connection point would be managed by wind farm pilot control system via the wind farm SCADA and each individual WTG unit. The active power set points normally received by the central control system would be dispatched to each WTG unit, controlling the active power and frequency locally. The wind farm design engineer would have to analyse responses at various generating levels, including those restricted at low wind speed conditions. For full load converter based wind farm applications the design engineer must be familiar with specifications, behaviour and limitations of the converter interfaces. In particular the DC link and the bridge converter would decouple the generator frequencies from the network (bridge) frequency, i.e. the system frequency. Therefore control of frequency would be managed by the network bridge converter and such principles may be invariant to applied variations in system frequencies. The design engineer must analyse if the frequency control functionality of full load converter topologies would satisfy the full range of requirements specified under the Rules. In particular the design engineer must consider limiters of converter and WTG equipment on active power reference signal changes. For DFIG units on the other hand, the power output can be controlled by the combination of the pitch and slip control of WTG units. Slip rings can be used to adjust and control rotor resistance and together with the blade pitch system, the power output can be controlled to a level determined by available wind. The design engineer should consider behaviour, analysis and any other technical limitations of the DFIG units, particularly those related to limitations of such slip ring control mechanisms. These systems are limited by the design which includes the Rectifier, Surge protective Equipment and IGBT switch.

For those requirements that cannot be met under this standard, the wind farm design engineer would have to negotiate appropriate approvals by NEMMCO and TSO for consideration of applicable performances of the WTG frequency control capabilities. The standard can be evaluated by way of mathematical models implemented in PSSE or PowerFactory Software. Typical set of studies would have to consider rises and flows in system frequency for which the following would normally be applied by TSO and are also suggested to be simulated by the wind farm design engineer: Generator tripping, and Load rejection, transient studies. In the case where expanded network information is not provided to the wind farm design engineer, then the frequency control injection tests (e.g. +/- 0.5Hz or higher) could be applied to WTG units in software simulation to assess performance with respect to this standard. This type of injection should be carried out at a number of MW output values, typically within the range boundaries of PMIN and PMAX. Performance requirements of the wind farm with respect to this standard are critical for maintenance of system security established under NEM, and compliance to this standard would be ongoing throughout the lifespan of the wind farm.

VII. Voltage and Reactive Power Control

The standard refers to requirements for control and settling response performances of WTG units. The standard is required to be analysed as part of R1 and R2 requirements, i.e. pre connection and post connection, respectively. Under this standard both R1 and R2 data must be compared and the WTG units, associated control and activations of limiters must conform such that active power, reactive power and voltage responses satisfy the following:

1. The settling time with the asynchronous unit online, following a disturbance equivalent to a 5 percent step change in the sensed generating unit voltage control point shall be less than 5 seconds. Typically this should be met at all operating points within the generating unit capability. Normally we may refer to generating unit terminal voltage, however it is design engineers responsibility to agree on type of a test with the TSO and NEMMCO for the purpose of providing enough data sufficient to establish dynamical operational characteristics of the WTG unit.

2. The settling time following any disturbance which causes any of the WTG limiter to operate shall be less than 7.5 seconds. The operating point should be such that 2.5% step would initiate the operation of the device. The design engineer must be aware of limiters and limiter protection functionalities for the control system tested in order to avoid trip of the unit.

3. WTG Control System must provide continuous *voltage* regulation to within 0.5 percent of the selected set-point value, and normally should be at all operating points within the generator capability. The standard normally specifies the value at POC.

4. The reactive power rise time should be less than 2 seconds for 5% step signal injections in the voltage reference summing junction of WTG unit.

5. The unit must be capable of set-point voltage control in the range of +/-5 % of normal voltage range at the point agreed between the wind farm design engineer and TSO. This requirement does not accept inclusion of any transformer tap changing capabilities.

6. The generating unit is adequately damped under all operating conditions.

7. Settling Time: The settling time for a step change is the time between the occurrence of the step and the instant that the difference between the initial (quantity) magnitude and its final value becomes (and remains) within ±10% of the overall change in the quantity magnitude.

Typically for large scale wind farm applications, Reactive Power and Voltage Control is realized via Pilot Control Scheme. Normally the wind farm would operate in the voltage control mode to provide for dynamic voltage support of the network. The voltage and reactive power is normally managed by SCADA loops which relate to WTG individual unit levels (i.e. control of voltage at 690V level) and the main SCADA system via central controller. The central control unit would need to monitor POC (or other point if agreed otherwise with TSO) and issue target voltage reference signals via dispatch instructions to individual WTG unit controls.

References

[1] AEMC, http://www.aemc.gov.au/

[2] AEMO, http://www.aemo.com.au/

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